STABILITY ANALYSIS FOR THE RIGHT ABUTMENT SPILLWAY
ISABELLA DAM CA

AEG Annual Meeting
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LRD Dam Safety Production Center
Dam Safety Modification Mandatory Center of Expertise

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STABILITY ANALYSIS FOR THE RIGHT ABUTMENT SPILLWAY – ISABELLA DAM, CA

OUTLINE

A. PROJECT INFORMATION
   1. Project Location
   2. Project Description
   3. Site Geology

B. SPILLWAY STABILITY
   1. Founding Elevations
   2. Plane Analysis
   3. Wedge Analysis

C. CUT-SLOPE STABILITY
   1. Stereonet Analysis
   2. Construction Concerns
Isabella Dam – Site Plan

**MAIN DAM**
- 185 ft high
- Zoned earth fill (almost homogeneous)
- Foundation primarily granitic bedrock

**AUXILIARY DAM**
- 100 ft high
- Homogeneous silty sand
- Foundation = alluvial soils and bedrock

**SPILLWAY**
- Ungated spillway
- Ogee Weir

**OUTLET WORKS**
- Hydropower

**Constructed 1948-1953**
Primary Purposes: Flood control (~74%); Irrigation (~21%); Non-Federal Hydropower (~5%)
Primary Issues – Potential Failure Modes

Erosion Through a Crack Near the Main Dam Crest

Kern Canyon Fault (Previous Interp: Inactive) Rupture Auxiliary Dam

Undersized spillway

Hydrologic Overtopping

Internal Erosion and Liquefaction Potential of the Foundation Alluvium

Erosion Along the Conduit

Seismic Stability of Borel Conduit and Tower

Cross Section – Kern Canyon Fault – Auxiliary Dam
Consequences of Dam Failure - Inundation

Vicinity Map

ISABELLA DAM

Immediate Inundation Area

Subsequent Inundation Area
Isabella Dam – Proposed Modifications

- **Main Dam**
- **Auxiliary Dam**
- **Existing Service Spillway**
- **Kern Canyon Fault**
Proposed Modifications – Emergency Spillway

Main Dam

Existing Service Spillway

Proposed Emergency Spillway

Kern Canyon Fault

Upstream

Labyrinth Weir

Emergency Spillway Physical Model
Proposed Modifications – Main Dam

- Raise Top of Main Dam by 16’
- Downstream Filter & Drain
Proposed Modifications – Main Dam

- Raise Top of Main Dam by 16'
- Downstream Filter & Drain

Main Dam
Auxiliary Dam
Proposed Emergency Spillway
Kern Canyon Fault
Proposed Modifications – Auxiliary Dam

- Raise Top of Auxiliary Dam by 16’
- Downstream Buttress with Filter & Drain

Section - Auxiliary Dam Inside Fault Zone

Section - Auxiliary Dam Outside Fault Zone
Proposed Modifications

- Raise Top of Main Dam by 16’
- Downstream Filter & Drain

- Raise Top of Auxiliary Dam by 16’
- Downstream Buttress with Filter & Drain
Proposed Modifications – Right Abutment Spillway

- Main Dam
- Right Abutment Spillway
- State Route 155
- SR 155
- Main Dam Raised 16’
- Flow

3D Image of Proposed Right Abutment Spillway

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Site Geology

- Cretaceous-aged Alta Sierra Granite
- Light gray, medium grained, hard
- Varying degrees of weathering
- Moderate to severely fractured

Mount Adelaide (early Cretaceous)

Alta Sierra (late Cretaceous)

Kern River Granite (late Cretaceous)

Right Abutment Spillway

Geologic Map – US Geologic Survey

Existing Service Spillway

Mount Adelaide (early Cretaceous)
Exploratory Drilling

Boring Location Plan

- Proposed Right Abutment Spillway
- Main Dam Raised 16'
- Inclined Boring
- Vertical Boring

Core Samples

Down-Hole Camera Images
**Granite - Weathering**

- **Decomposed Granite:** reddish brown, soft, soil-like with relic bedrock structure, under 2,000 psi UCS.

- **Highly Weathered Granite:** light reddish brown, soft to moderately hard, individual grains can be easily plucked with a knife, 2,000 – 8,500 psi UCS. Predominant rock type at spillway site.

- **Moderately Weathered Granite:** light reddish gray, moderately hard to hard, difficult to pluck individual grains with a knife, 8,500 to 10,000 psi UCS.

- **Slightly or Unweathered Granite:** Light gray, hard, 10,000 to 25,000 psi UCS.

Boring F1-13-15 Showing Varying Degrees of Weathering
Discontinuities

- **Typical Fracture**: planar shape; smooth surface; occasionally open, iron stained or clay coated; and continuous (10' to +100' length)
- **Distinct Joint Sets (A - K)**
- **Moderate to intensely fractured**
- **Shear Zones**
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Potential Spillway Erosion - Consequences

Isabella Dam – Right Abutment Spillway

Oroville Dam - Spillway Erosion
Right Abutment Spillway - Design

Plan View

Profile View
Foundation Elevation – Typical Upstream of Dam Monolith

- Foundation surface will be free of all soil, Decomposed Granite and loose rock.
- Foundation geometry will consist of stair-stepped series of horizontal surfaces.
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- Foundation geometry will consist of stair-stepped series of horizontal surfaces.
Founding Elevation – Typical Downstream Monolith

- Foundation surface will be free of all soil, Decomposed Granite and loose rock.
- Foundation geometry will consist of stair-stepped series of horizontal surfaces.

Approximate Base of Near-Surface Decomposed Granite

Preliminary Foundation Elevations

Foundation Drain

Spillway

Top of Ground

Foundation Concrete

Temporary Detour Road

Boring F1-16-04

DRAIN

HW

DG

MW

SW

UW

Soil

Decomposed Granite

Highly Weathered Granite

Moderately Weathered Granite

Slightly Weathered Granite

Unweathered Granite

Cross Section – Station 104+20

-100 -80 -60 -40 -20 0 20 40 60 80 100

2560 2580 2600 2620 2640 2660 2680

30 40 50 60 70 80 90
Final foundation elevations will be established in the field.

- Experienced on-site geologist is required.
- Localized problematic areas are expected.
- Dental concrete may be required.
Spillway Structure - Design Details

Expansion Joint Detail

Section - Downstream - Foundation Drain

Joint Drain Detail

Profile View
Planar Sliding Stability – Input Parameters

- Sliding Resistance for Highly Weathered Granite:
  phi = 33 degrees, cohesion = 0 psi

- 5 degree waviness or i angle (as measured in field)

- Maximum design earthquake: horizontal PGA 0.3g, vertical PGA 0.21g. Seismic coefficient 0.2 (2/3 of 0.3g)
Planar Sliding – Downstream Monolith – Load Cases

<table>
<thead>
<tr>
<th>Load Case 14° Plane</th>
<th>Loading Condition</th>
<th>Required Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Joints no uplift</td>
<td>Usual</td>
<td>1.5</td>
</tr>
<tr>
<td>Rain - Wet Joints full uplift</td>
<td>Unusual</td>
<td>1.3</td>
</tr>
<tr>
<td>Flood PMF full uplift</td>
<td>Extreme</td>
<td>1.1</td>
</tr>
<tr>
<td>Earthquake MDE no uplift</td>
<td>Extreme</td>
<td>1.1</td>
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Cross Section – Downstream of Dam – 14° Plane

Potential Failure Plane (47.8’ length, 14 degree inclination)
Approximate Base of Near-Surface Decomposed Granite
Uplift - Groundwater
Top of Ground
Spillway

Dry Joints no uplift
Usual
Unusual
Extreme
Extreme
1.5
1.3
1.1
1.1
Planar Sliding – Downstream Monolith – Load Cases

<table>
<thead>
<tr>
<th>Load Case 20° Plane</th>
<th>Loading Condition</th>
<th>Required Factor of Safety</th>
</tr>
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<tbody>
<tr>
<td>Dry Joints no uplift</td>
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<td>1.5</td>
</tr>
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<td>1.1</td>
</tr>
<tr>
<td>Earthquake MDE no uplift</td>
<td>Extreme</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Cross Section – Downstream of Dam – 20° Plane

Top of Ground

Potential Failure Plane (109’ length, 20 degree inclination)

Approximate Base of Near-Surface Decomposed Granite

Spillway
Planar Sliding – Dam Crest – Load Cases - Construction

<table>
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<tr>
<th>Load Case 20° Plane</th>
<th>Loading Condition</th>
<th>Required Factor of Safety</th>
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<td>Unusual</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Approximate Base of Near-Surface Decomposed Granite

Potential Failure Plane (47.8’ length, 14 degree inclination)

Top of Ground

Uplift - Groundwater

Spillway

DRAIN

Dam Embankment
2D Planar Sliding Equation

$$FS = \left[ \left( (W \cos(\beta + \epsilon) - U - V \sin(\beta)) \tan(\phi_w) \right) + ((W \cos(\beta + \epsilon) - U - V \sin(\beta)) \tan(\phi_w)) + cL \right] / \left( (W \sin(\beta + \epsilon)) + (V \cos(\beta)) \right)$$

WHERE: $Z =$ tension joint height, $Z_w =$ water height in tension joint, $\beta_p =$ dip angle of discontinuity, $\gamma_w =$ unit weight of water, $c =$ cohesion (Highly Weathered Granite = 0 psf), $\phi =$ bedrock friction angle (Highly Weathered Granite = 33$^\circ$), $\phi_w =$ waviness angle of bedrock discontinuity (5$^\circ$ measured at site), $L =$ length of discontinuity, $W =$ weight of block, $U =$ uplift forces [$U = 1/2 \ L \ Z_w \ \gamma_w$], $V =$ horizontal forces [$V = 1/2 \ Z_w \ ^2 \ \gamma_w$], $k =$ Seismic Coefficient (MDE), $\epsilon =$ angle of resultant seismic force [$\epsilon =$ atan ($k$)], $FS =$ factor of safety

* Seismic influence is derived from EM 1110-1-2907, section 3-11.b.4.e, equation (1).
## 2D Planar Sliding Stability – Summary & Sensitivity

<table>
<thead>
<tr>
<th>Load Case *</th>
<th>Loading Condition</th>
<th>Required FS</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolith M-6, during construction, w/o hydrostatic pressure, dry</td>
<td>Usual</td>
<td>1.5</td>
<td>2.96</td>
</tr>
<tr>
<td>Monolith M-6, during construction, full hydrostatic pressure, wet</td>
<td>Unusual</td>
<td>1.3</td>
<td>1.98</td>
</tr>
<tr>
<td>Monolith M-12, 45° failure plane, w/o hydrostatic pressure, dry</td>
<td>Usual</td>
<td>1.5</td>
<td>2.96</td>
</tr>
<tr>
<td>Monolith M-12, 45° failure plane, full hydrostatic pressure, wet</td>
<td>Unusual</td>
<td>1.3</td>
<td>2.15</td>
</tr>
<tr>
<td>Monolith M-12, 45° failure plane, full hydrostatic pressure, PMF flow</td>
<td>Extreme</td>
<td>1.1</td>
<td>2.26</td>
</tr>
<tr>
<td>Monolith M-12, 45° failure plane, w/o hydrostatic pressure, seismic MDE</td>
<td>Extreme</td>
<td>1.1</td>
<td>1.56</td>
</tr>
<tr>
<td>Monolith M-12, 20° failure plane, w/o hydrostatic pressure, dry</td>
<td>Usual</td>
<td>1.5</td>
<td>2.02</td>
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<tr>
<td>Monolith M-12, 20° failure plane, full hydrostatic pressure, wet</td>
<td>Unusual</td>
<td>1.3</td>
<td>1.53</td>
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<tr>
<td>Monolith M-12, 20° failure plane, full hydrostatic pressure, PMF flow</td>
<td>Extreme</td>
<td>1.1</td>
<td>1.57</td>
</tr>
<tr>
<td>Monolith M-12, 20° failure plane, w/o hydrostatic pressure, seismic MDE</td>
<td>Extreme</td>
<td>1.1</td>
<td>1.21</td>
</tr>
</tbody>
</table>

* All load cases incorporate a 33° sliding friction angle (Highly Weathered Granite) and 5° “waviness” (θ₀, or i) angle (as measured in field).
### 3D Wedge Analysis

#### Major Joint Sets, average orientations

<table>
<thead>
<tr>
<th>Wedges</th>
<th>Dip</th>
<th>Dip Direction</th>
<th>% of Total No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>88</td>
<td>149</td>
<td>16</td>
</tr>
<tr>
<td>B</td>
<td>90</td>
<td>112</td>
<td>11</td>
</tr>
<tr>
<td>C</td>
<td>23</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>D</td>
<td>81</td>
<td>228</td>
<td>7</td>
</tr>
<tr>
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<td>14</td>
</tr>
<tr>
<td>I</td>
<td>70</td>
<td>270</td>
<td>14</td>
</tr>
</tbody>
</table>

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**Right Abutment Spillway**

**Main Dam Raised 16’**

**Wedge - Two Joints w/ Tension Plane**

**Hypothetical Wedge**
Detrimental Wedges

Utilized Swedge program from Rocscience

Two detrimental wedges: Joint Sets A&C, Joint Sets D&E

Sliding resistance of Highly Weathered Granite: \( \phi = 33^\circ, c = 0 \)

psi w/ 5° waviness added
Joint Sets D&E
With Tension Plane

Joint Sets D&E
W/O Tension Plane

Joint Sets A&C
With Tension Plane

Joint Sets A&C
W/O Tension Plane
Wedge Analysis – Load Cases

- **Dry Joints**
  - Usual

- **Rain Event**
  - Water Filled Joints
  - Unusual

- **PMF Flood**
  - Water Filled Joints
  - Extreme

- **MDE Earthquake**
  - Dry Joints
  - Extreme
## 3D Wedge Stability – Summary & Sensitivity

**Factor of Safety for Wedge Analysis**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Required Factor of Safety</th>
<th>Factor of Safety (from Swedge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D&amp;E w/ tension plane - Usual (dry) Condition</td>
<td>1.5</td>
<td>4.93</td>
</tr>
<tr>
<td>D&amp;E w/ tension plane - Unusual (wet) Condition</td>
<td>1.3</td>
<td>2.03</td>
</tr>
<tr>
<td>D&amp;E w/ tension plane - Extreme (PMF-wet) Condition</td>
<td>1.1</td>
<td>2.07</td>
</tr>
<tr>
<td>D&amp;E w/ tension plane - Extreme (MDE-dry) Condition</td>
<td>1.1</td>
<td>2.34</td>
</tr>
<tr>
<td>D&amp;E w/o tension plane - Usual (dry) Condition</td>
<td>1.5</td>
<td>4.93</td>
</tr>
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<td>D&amp;E w/o tension plane - Unusual (wet) Condition</td>
<td>1.3</td>
<td>2.93</td>
</tr>
<tr>
<td>D&amp;E w/o tension plane - Extreme (PMF-wet) Condition</td>
<td>1.1</td>
<td>3.30</td>
</tr>
<tr>
<td>D&amp;E w/o tension plane - Extreme (MDE-dry) Condition</td>
<td>1.1</td>
<td>2.58</td>
</tr>
<tr>
<td>A&amp;C w/ tension plane - Usual (dry) Condition</td>
<td>1.5</td>
<td>3.78</td>
</tr>
<tr>
<td>A&amp;C w/ tension plane - Unusual (wet) Condition</td>
<td>1.3</td>
<td>2.33</td>
</tr>
<tr>
<td>A&amp;C w/ tension plane - Extreme (PMF-wet) Condition</td>
<td>1.1</td>
<td>2.39</td>
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<td>2.47</td>
</tr>
<tr>
<td>A&amp;C w/o tension plane - Extreme (MDE-dry) Condition</td>
<td>1.1</td>
<td>2.10</td>
</tr>
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<td>1.1</td>
<td>2.56</td>
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**Sensitivity – Wedge D&E w/ Tension Plane (wet)**
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Cut-Slope Stability

Cross Section – Station 102+90

- Raised Dam Embankment
- Dam Embankment
- Approximate Base of Near-Surface Decomposed Granite
- Approximate Top of Rock
- Spillway
- Preliminary Foundation Elevations
- Foundation Concrete
- Top of Ground
- Cut-Slope

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Kinematic Analysis – Input Parameters

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Existing Slope

Sliding Resistance for Highly Weathered Granite:
\[ \phi = 33 \text{ degrees}, \text{ cohesion} = 0 \text{ psi} \]
Stereographic Projection – Planar Failure

West Side Cut Slope ½:1

East Side Cut Slope ½:1
Stereographic Projection – Wedge Failure

West Side Cut Slope ½:1

East Side Cut Slope ½:1
Stereographic Projection – Toppling Failure

West Side Cut Slope $\frac{1}{2}:1$

East Side Cut Slope $\frac{1}{2}:1$
Future Construction Concerns

- Overhead boulders or rock fall during excavation.
- Mechanical excavation methods
- Joints with detrimental orientations and low sliding resistance (clay filled or fault gouge)
- Localized problematic areas of Decomposed Granite.
- Experienced on-site geologist is required

Construction Contract Status

- Plans and Specifications completed
- Advertised and Bids received
- Notice to Proceed - soon
- Approximately 4 years to construct
1. Sliding stability for structures can be determined by utilizing equations and methods typically used for cut-slope design. (If the proposed structure is on the side of a hill)

2. Bedrock weathering can have significant impact on rock strength and influence structural design.

3. How can anyone can talk so much about such a small project?
Stability Analysis for the Right Abutment Spillway
Isabella Dam, CA

QUESTIONS